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## Abstract

The interactions between exhaust plumes and the ambient, high altitude atmosphere have been investigated by the components of the Department of Defense for many years. To date, laboratory investigations of space plumes from firing thrusters and simulated ambient environments have been difficult to achieve due to limitations in pumping speed. The major limitation of ground-based facilities in accurately predicting the effects of thruster operation on spacecraft systems has always been driven by the facility's background pressure. The Chamber-IV of the David P. Weaver Collaborative High Altitude Flow Facility (CHAFF-IV) at the University of Southern California is used for such investigations. One of the critical components of the CHAFF-IV pumping system is a cryogenic helium refrigerator (or cryostat) that supplies gaseous helium at 15 – 20 K to the pumping panels. Higher speed CHAFF-IV pumping for both chemical and electric thrusters allows accurate thruster interaction studies to be performed through the addition of a high capacity commercially available cryostat. Significant increases (approximately a factor of 5) in the pumping speed allows for higher power thrusters (on the order of 10 – 15 kW) to be operated in the facility. This addition satisfies recent interest in very high power electric ion thrusters and also high flow rate chemical engines operating on advanced (higher temperature) propellants. Additionally, it allows for multiple small thrusters to be fired simultaneously to simulate microspacecraft platoon or constellation formation and operations.

# FINAL REPORT (F49620-01-1-0241)

## Significant Increase in the Cryogenic Pumping System Capacity and Reliability for the CHAFF-IV Plume and Contamination Facility

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### Abstract

The interactions between exhaust plumes and the ambient, high altitude atmosphere have been investigated by the components of the Department of Defense (e.g. the Air Force, Army, and Ballistic Missile Defense Organization) for many years. To date, laboratory investigations of space plumes from firing thrusters and simulated ambient environments have been difficult to achieve due to limitations in facility design. Facilities must faithfully and consistently reproduce the space environment to be of any real use. To date, this has been a major challenge for all interaction facilities. The major limitation of ground-based facilities in accurately predicting the effects of thruster operation on spacecraft systems has always been driven by the facility's background pressure. In order to provide the level of pumping required for meaningful thruster interactions, cryogenic condensation panels covering the entire inner surface of the facility are required. With these facility requirements in mind, Chamber-IV of the David P. Weaver Collaborative High Altitude Flow Facility (CHAFF-IV) has been constructed at the University of Southern California. One of the critical components of the CHAFF-IV pumping system is the cryogenic helium refrigerator (or cryostat) that supplies gaseous helium at 15 – 20 K to the pumping panels. Higher capacity and more reliable CHAFF-IV pumping for both chemical and electric thrusters allows accurate thruster interaction studies to be performed through the addition of a commercially available cryostat. Additional cryogenic pumping also allows for future ambient atmospheric flow simulation additions to the facility such as atomic oxygen, plasma, and solar spectral sources. Significant increases (approximately a factor of 5) in the pumping capacity can be obtained, which allows for higher power thrusters (on the order of 10 – 15 kW) to be operated in the facility. This addition satisfies recent interest in very high power electric ion thrusters and high flow rate chemical engines operating on advanced (higher temperature) propellants. It also allows for multiple small thrusters to be fired simultaneously to simulate microspacecraft platoon or constellation formation and operations.

## Executive Summary

- The David P. Weaver Collaborative High Altitude Flow Facilities (CHAFF) was designed to permit studies of the interactions with the space environment of propulsion plumes (both chemical and electric) and contamination transport and deposition. CHAFF provides a user friendly set of facilities with tolerable operating expenses on the scale of University-based defense and commercial application research.

- CHAFF is available to Government Laboratory, Industrial and University researchers. It's intent is to encourage University researchers and students to become involved with defense research in areas that have been largely inaccessible due to the cost of operating typically large space simulation chambers, which are also generally technically unattractive for scientific experiments.

- In order to provide the level of pumping required for meaningful thruster interactions, cryogenic condensation panels covering the entire inner surface of the facility are required. With these facility requirements in mind, Chamber-IV of the David P. Weaver Collaborative High Altitude Flow Facility (CHAFF-IV) has been constructed at the University of Southern California (USC). The major design objectives of the CHAFF-IV facility and the unique cryogenic pumping system were:

    - suppression of gas-facility boundary effects, only possible using cryogenic pumping on essentially the entire inner surface of the facility
    - ability to pump several grams per second of propulsion gases while maintaining adequate background pressures to ensure meaningful data (section 1.3)
    - generation of typical high altitude ambient gas flows including ionospheric plasma, atomic oxygen, and solar simulation
    - provide convenient access for modern diagnostic instruments
    - sufficiently reasonable operating cost

- One of the critical components of the CHAFF-IV pumping system is the cryogenic helium refrigerator (or cryostat) that supplies gaseous helium at 15 – 20 K to the pumping panels.

- The helium cryostat procured with the present DURIP award provides more reliable CHAFF-IV pumping for both chemical and electric thrusters that allowing accurate thruster interaction studies to be performed.

- Additional cryogenic pumping also allows for future ambient atmospheric flow simulation additions to the facility such as atomic oxygen, plasma, and solar spectral sources.

- Significant increase (approximately a factor of 5) in the pumping capacity is obtained, which permits higher power thrusters (on the order of 10 – 15 kW) to be operated in the facility. This addition satisfies recent interest in very high power electric ion thrusters and high flow rate chemical engines operating on advanced (higher temperature) propellants.

- It also allows for multiple small thrusters to be fired simultaneously to simulate microspacecraft platoon or constellation formation and operations.

## 1 INTRODUCTION

The interactions between exhaust plumes and the ambient, high altitude atmosphere have been investigated by the components of the Department of Defense (e.g. the Air Force, Army, and Ballistic Missile Defense Organization) for many years. To date, laboratory investigations of space plumes from firing thrusters and simulated ambient environments have been difficult to achieve due to limitations in facility design. Many experimental results obtained to date are for energetic species interacting with gas clouds used to simulate rocket plumes. Although ground-based flow investigations cannot approach all segments of the plume-ambient atmosphere interaction problem, several key scientific questions can be investigated in a facility which provides high fidelity experimental reproduction of high altitude regimes including low facility pressure, appropriate flow energies, atomic oxygen flux, ionospheric plasma flow, and solar radiation.

In addition, the interactions between on-board spacecraft propulsion systems and spacecraft surfaces has received considerable attention in recent years from Department of Defense, NASA, and commercial investigators. The impact of potential interactions to spacecraft is becoming more critical as mission life and payload sensitivity requirements are continually increased. The adsorption of propellant gases on spacecraft surfaces (often referred to as contamination) can change solar absorptivity of thermal control surfaces, alter reflectivity of optical surfaces, alter transmission through solar cell coverglass, and induce environments which can alter scientific results. There are several classes of sensitive military and scientific spacecraft that would benefit from propulsive attitude control but which will not allow on-board propulsion systems due to contamination concerns (for example the recent MSX spacecraft and the proposed Space-Based Infra-Red (SBIR) satellites). The growing popularity of electric ion propulsion systems due to their high specific impulse operation promises renewed interest in this area of research. Ion electric thrusters add further complications due to material sputtering from high energy ion (propellant) impact and the possible alteration of spacecraft potentials.

Although the Space Shuttle has made an attempt to make space-based investigations more feasible by providing a "reliable" space platform and the capability of returning payloads to Earth for careful examination, the reality is that the cost of space-based experiments is still quite high. Space-based experiments can also be extremely limited in scope due to a lack of available instrumentation, geometrical variation, accurate detail of the time-dependent space environment, and on-orbit time. It is clear that ground-based examination of thruster interactions with the ambient environment and spacecraft surfaces is necessary to compliment the sometimes limited data returned from space experiments.

Some of the immediate advantages to having ground-based facilities include the reduced cost of obtaining data, the ability to change experimental configurations, the ability to perform tests with a large number of material samples, the ability to perform accelerated testing for material certification, and the availability of a greater array of diagnostic tools. Facilities must faithfully and consistently reproduce the space environment to be of any real use. To date, this has been a major challenge for all interaction facilities.

The major limitation of ground-based facilities in accurately predicting the effects of thruster operation on spacecraft systems has always been driven by the facility's background pressure. There are at least three components of the background pressure with which a facility must contend. Although some fraction of the background gas is composed of the residual laboratory atmosphere, the largest complication can arise from the fact that the overwhelming majority of the background gas is thruster derived. These thruster-borne components of the background gas are largely responsible for experimental measurement errors as will be discussed in the following sections. Besides the thruster effluents and residual atmosphere, ion electric thrusters can also produce a third background population of sputtered products due to high energy ion impact with thruster and chamber surfaces.

The effects of the residual atmosphere can be minimized by operating the facility at very low ultimate pressure. Although achieving low ultimate pressure in a large vacuum facility can be difficult, minimizing the effects of thruster-born effluents is much more complicated since extremely high pumping rates are required. Therefore, improvements to the accuracy of ground-based data come at the cost of more efficient chamber pumping.

In order to provide the level of pumping required for meaningful thruster interactions, cryogenic condensation panels covering the entire inner surface of the facility are required. With these facility requirements in mind, Chamber-IV of the David P. Weaver Collaborative High Altitude Flow Facility (CHAFF-IV) has been constructed at the University of Southern California (USC). The major design objectives of the CHAFF-IV facility and the unique cryogenic pumping system were:

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One of the critical components of the CHAFF-IV pumping system is the cryogenic helium refrigerator (or cryostat) that supplies gaseous helium at 15 – 20 K to the pumping panels. The new cryostat provides higher capacity and more reliable CHAFF-IV pumping for both chemical and electric thrusters, which allows accurate thruster interaction studies to be performed. Significant increases (approximately a factor of 5) in the pumping capacity can be reliably obtained which allows higher power thrusters (on the order of 10 – 15 kW) to be operated in the facility. This addition satisfies recent interest in very high power electric ion thrusters and high flow rate chemical engines operating on advanced (higher temperature) propellants. It also allows for multiple small thrusters to be fired simultaneously to simulate microspacecraft platoon or constellation formation and operations.

The additional pumping capacity also makes possible the addition of flow sources for the simulation of the ambient spacecraft environment. Relatively high flux rates of atomic oxygen, plasma and the addition of high power solar simulators place demands on available pumping. The introduction of these highly energetic flows will require similar pumping requirements as the thrusters that are operating simultaneously. Many of the sources require differential pumping from the main chamber to assure flow quality. These demands are met by the addition of the new cryostat.

### 1.1 Special Facility Issues Associated with Nozzle Expansions and Chemical Thrusters

Nozzle expansions are typically operated at relatively large Reynolds numbers in an attempt to maintain propulsive efficiency. This can translate to very high propellant mass flow rates expanding into a ground-based facility. Nozzle expansion thrusters (chemical and electrothermal) are typically used on spacecraft for high thrust orbital maneuvering and attitude control. It is interesting to note that the penetration distance of the plume into the background facility gas can be quite large for a high pressure ratio nozzle expansion. In other words, penetration of the background gas into the plume occurs only after several nozzle diameters downstream of the exit plane.

The resulting plume flow for a nozzle expansion in space and ground-based facilities is shown in Fig. 1. As is evident, the background pressure and composition for studying nozzle expansions in the core of the flow (inside dashed line in Fig. 1(a)) are not particularly critical. However, details of the far-field (several nozzle diameters downstream) interaction between the nozzle flow and the ambient environment relies heavily on the facility background pressure.

For interaction studies between nozzle expansions and spacecraft surfaces, the background pressure is absolutely critical for two reasons. First, the fluid mechanical nature of the impinging flow on a surface is fundamentally different for continuum and free molecule conditions near a wall. In space, the entire range of continuum flow through transition and subsequent free molecule flow is experienced. This must be faithfully reproduced in ground-based facilities which again indicates that low background pressures are needed to satisfy the free molecule condition.[1]

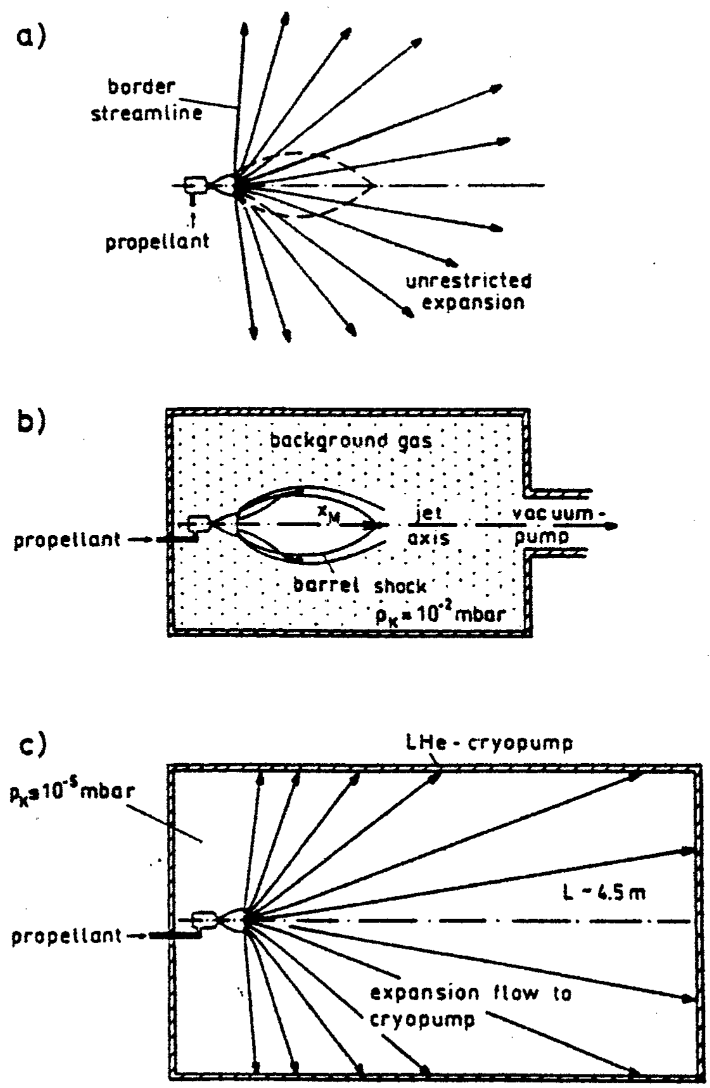


**Figure 1:** Plume expansion. a) In space; b) in vacuum chamber with conventional pumping scheme, c) in vacuum with cryogenic total chamber pumping scheme.

The second reason for desired low background pressure facility operation with nozzle expansions is plume backflow depicted in Fig. 2. The plume backflow is primarily determined by a thin subsonic boundary layer near the nozzle lip. The boundary layer can turn sharply at the lip while undergoing expansion. Once in the backflow region, the flow very quickly becomes free molecular.[2] Again, to faithfully reproduce nozzle backflow characteristics in ground-based facilities, low operating background pressure and efficient pumping of exhaust species is required.

Figure 1 (c) shows the benefits of a concept referred to as total chamber pumping (TCP).[3] In this configuration, the facility pumping system covers the entire inner surface of the facility. Perhaps the only effective way to achieve TCP is through cryogenic pumping of panels lining the facility walls. Because of the high flow rates exhausting from nozzle expansion thrusters, effective cryopumping can be difficult to maintain. Depending on the propellant mass flow, the heat flux from the propellant gases to the cryogenic arrays can be quite high and can easily overwhelm the capacity of a typical cryostat. Specially designed cryo-panel arrangements are required to handle these heat loads.

There are several other special issues associated with the ground-based testing of nozzle expansion thrusters. Among these is pumping relatively large amounts of hydrogen formed during the combustion process of chemical thrusters. Hydrogen is difficult to pump cryogenically without the aid of cryosorption material (zeolite) or effective sublimation pumping. The pumping of large amounts of incondensable gases is required to maintain low facility background pressures.

Also, plume contamination on spacecraft surfaces due to self scattering (propellant molecules colliding in the plume) can be important for sensitive subsystems.[4] For these studies, sufficiently low background pressures are required which do not significantly increase the propellant's collision probability in the plume at reasonable distances downstream of the thruster exit plane.

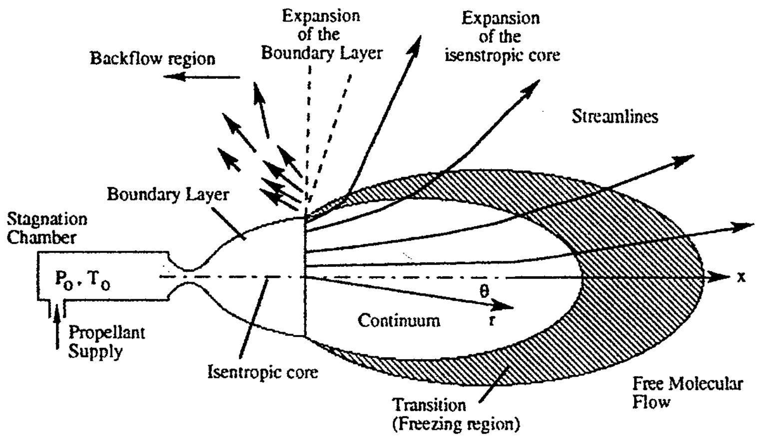


**Figure 2:** Flow types from continuum to free molecular regimes in a plume expanding into vacuum.

### 1.2 Special Facility Issues Associated with Ion Electric Propulsion Systems

In most Hall Effect and gridded ion thrusters, the background gas in a facility is able to penetrate freely up to exit plane of the thruster due to the rarefied nature of the plume flow. Investigations of ion electric thruster operations in ground-based facilities are likely to be extremely sensitive to facility induced background populations. In fact, such effects may be very subtle since the propellant gas (in most cases xenon) is the same as the generated background gas.

*Entrained Gas Flow*

With a xenon background gas capable of penetrating to the thruster exit plane, background gas can be entrained into the discharge region of the thruster and re-used as propellant. This can result in performance enhancement since the effective thrust is increased without accounting for the increase in propellant mass flow.[5] Since the entrainment flux of background gas to the thruster is proportional to the background gas number density, adequate pumping is required to reduce its effects on performance measurements. Previous studies[5] suggest that the entrained mass flow rate should be less than 3% of the injected propellant flow rate to obtain accurate measurements. From a simple analysis, it is found that the chamber pressure should be below $5 \times 10^{-5}$ Torr to ensure this condition.

The entrainment of background gases has also been observed to induce discharge oscillations which can severely degrade thruster performance.[6] These oscillations can occur at background pressures of approximately $3 \times 10^{-5}$ Torr. The obvious recommendation is to maintain facility background pressures below this value.

*Charge Exchange*

In the single charge exchange process, a fast moving ion from the thruster discharge interacts with a relatively slow moving neutral atom or molecule exchanging their charge and a small amount of kinetic energy. The result is a fast moving neutral atom and a slow ion from the reaction

$$X^{+}_{fast} + Y_{slow} \rightarrow X_{fast} + Y^{+}_{slow} + \Delta E \qquad \text{(R1)}$$

where $\Delta E$ is the energy defect of the process or the difference of the two atoms ionization potential. In the case of a fast xenon ion expelled into a slow xenon background gas, the energy defect is zero. This condition is known as a resonant charge exchange, and the cross section for resonant charge exchange collisions $\sigma_{cex}$ can be quite large. Recent results[7] give a charge exchange cross section for xenon ions at 300 eV energies with thermal xenon atoms of 55 Å$^2$.

Because the background number densities in ground-based facilities is much larger than experienced on-orbit, dramatic increases in charge exchange collisions are expected. Increased charge exchange collisions in ground-based facilities can cause two fundamental problems in trying to assess plume interaction effects. First, the primary ions in the main thruster beam will be depleted by

$$I_{cx} = I_o \exp(-n_b \sigma_{cex} x) \qquad (1)$$

where $I_{cx}$ is the primary ion current collected at an axial position x downstream of the exit plane, $I_o$ is the primary ion current at the exit plane, and $n_b$ is the background gas number density. For a background pressure of 5 x $10^{-5}$ Torr, a primary xenon ion beam 1 m downstream of the thruster exit plane is expected to be reduced by over 55% of the initial beam current.

The second major effect of increased charge exchange collisions in ground-based facilities is the creation of more slow moving ions. It is generally known that slow moving charge exchange ions are capable of being transported back towards spacecraft.[8] The relatively low energy charge exchange ions can be influenced by local electric fields in the plume and near spacecraft. The creation of charge exchange ions for the case of fast ions impinging on a slow background gas target is given by

$$d(n_{is}) = (n_{if} \sigma_{cex} - n_{is} \sigma_r) d(I_n) \qquad (2)$$

where $n_{is}$ is the number density of slow ions, $n_{if}$ is the number density of fast ions, $\sigma_r$ is the recombination cross-section and $I_n$ is the column depth of background gas (line-of-sight integrated number density).

For resonant charge exchange collisions at relatively low pressures, $\sigma_{cex} \gg \sigma_r$ due to the lack of 3-body collisions in the plume. It has also been found that the collision (or momentum transfer) cross section for xenon ions colliding with neutral xenon is an order of magnitude smaller than $\sigma_{cex}$.[9] Based on these assumptions, the solutions to Eqn. (2) are relatively straight forward. Figure 3 shows the ratio of charge exchange ions to primary ions as a function of downstream distance from the thruster exit plane for various background pressures. As shown in Fig. 3, the charge exchange population of slow ions increases dramatically for increased background density quite close to the thruster exit plane. For this reason, interaction studies which investigate the effects of charge exchange ions in the backflow regions must be carried out at very low background pressures.

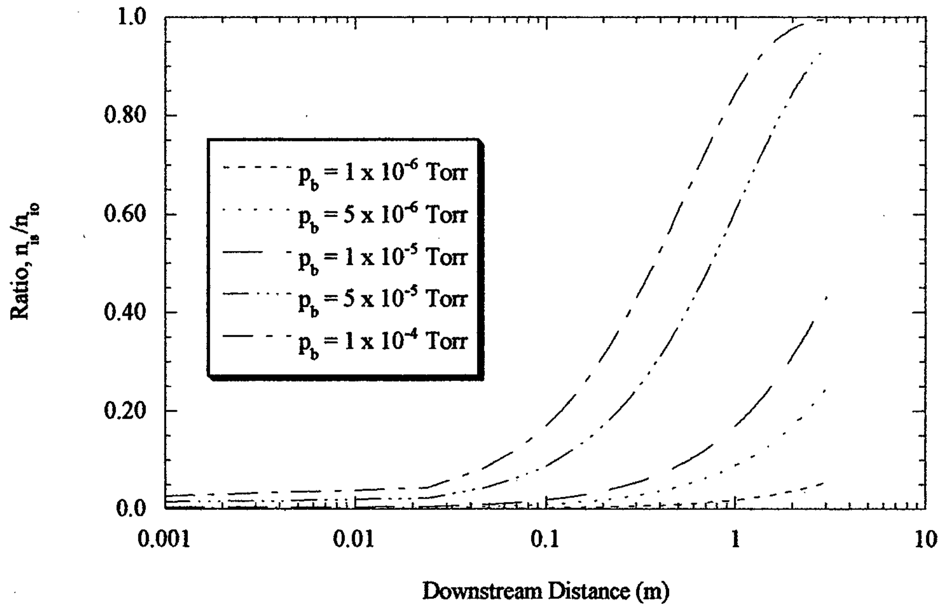


**Figure 3:** Fraction of charge exchange ions to primary ions as a function of distance from an ion thruster exit plane and background pressure.

### 1.3 Facility Design Issues

In a typical ground-based facility with a fraction $f_p$ of its inner surface occupied by pump inlets or pumping surface, the thruster effluents are generally stopped and randomized by the facility's surfaces. The random motion of the scattered propellant molecules drives them into the pump inlets or to a pumping surface. The background number density of propellant gas in a facility can be approximated by

$$n_b = \frac{4\dot{M}\left(\frac{T_p}{T_b}\right)^{\frac{1}{2}}}{m_p v' f_p A_s} \tag{3}$$

where $\dot{M}$ is the propellant mass flow, $T_p$ is the propellant temperature, $T_b$ is the background gas temperature, $m_p$ propellant molecular mass, and $A_s$ is the inner surface area of the chamber.

As previously mentioned, the driving factor for ground-based thruster interaction studies is low background pressure. The facility background pressure can be found by

$$P_b = \frac{\dot{M}_p kT_b}{m_p \dot{V}} \tag{4}$$

where $\dot{V}$ is the chamber pumping speed, and k is Boltzmann's constant. Figure 6 shows the expected pumping speed to maintain a given background pressure for a typical Hall thruster (~5 mg/sec of xenon) and a cold gas thruster (~1 g/sec of nitrogen). As indicated in Fig. 4, a pumping rate of approximately 2.5 x $10^4$ L/sec is required to maintain a background pressure below 3 x $10^{-5}$ Torr for the xenon ion thruster. This can be readily achieved in several existing facilities making them suitable for performance testing.[5] However for interaction studies where chamber induced charge exchange collisions must be negligible, an

order of magnitude lower background pressure is desired.[3] This dictates a pumping rate of at least 2.5 x $10^5$ L/sec.

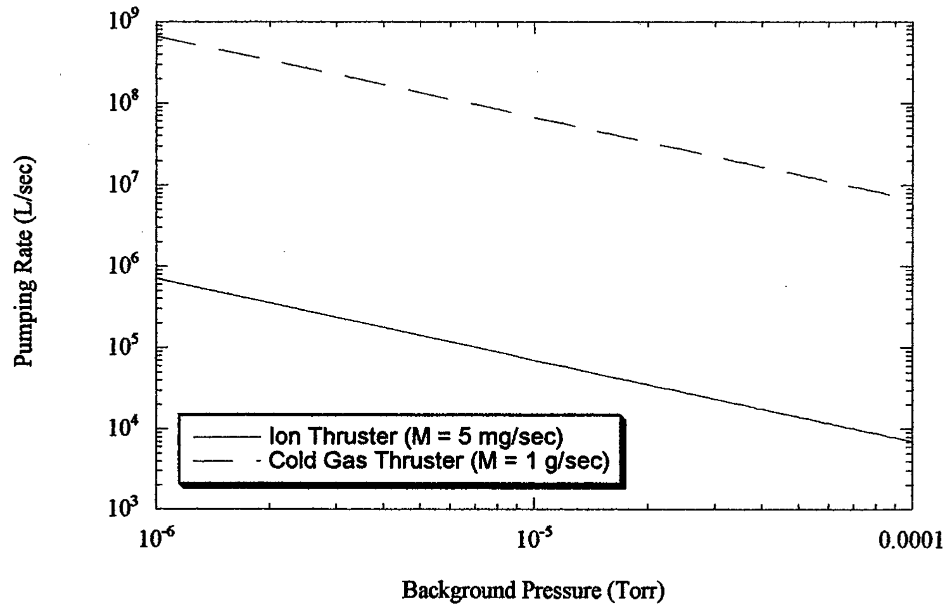


**Figure 4:** Facility pumping speed to maintain a given background pressure for a typical Hall thruster flow (Xe) and cold gas thruster ($N_2$).

For the cold gas system, pumping rates on the order of $10^7$ L/sec are required to maintain pressures in the $10^{-5}$ Torr range. Pressures on this order are critical to perform high fidelity backflow measurements by maintaining free molecular flow in the plume backflow region.

Clearly a critical background number density for thruster plume interaction studies is reached when the background mean free path becomes less than or equal to the largest internal dimension of the facility $L_c$. Therefore, the background number density should be kept at or below

$$n_b \le \frac{1}{\sqrt{2}\sigma_b L_c} \tag{5}$$

where $\sigma_b$ is the background gas collision cross section. For a xenon background gas, the background number density should be $n_b \le 7 \times 10^{18} (L_c)^{-1}$.

## 2 CHAFF-IV PLUME AND CONTAMINATION FACILITY

The David P. Weaver Collaborative High Altitude Flow Facilities (CHAFF) was designed to permit studies of the interactions with the space environment of propulsion plumes (both chemical and electric) and contamination transport and deposition. CHAFF provides a user friendly set of facilities shown in Fig. 5 with tolerable operating expenses on the scale of University-based defense and commercial application research. It is available to Government Laboratory, Industrial and University researchers. It's intent is to encourage University researchers and students to become involved with defense research in areas that have been largely inaccessible due to the cost of operating typically large space simulation chambers, which are also generally technically unattractive for scientific experiments.

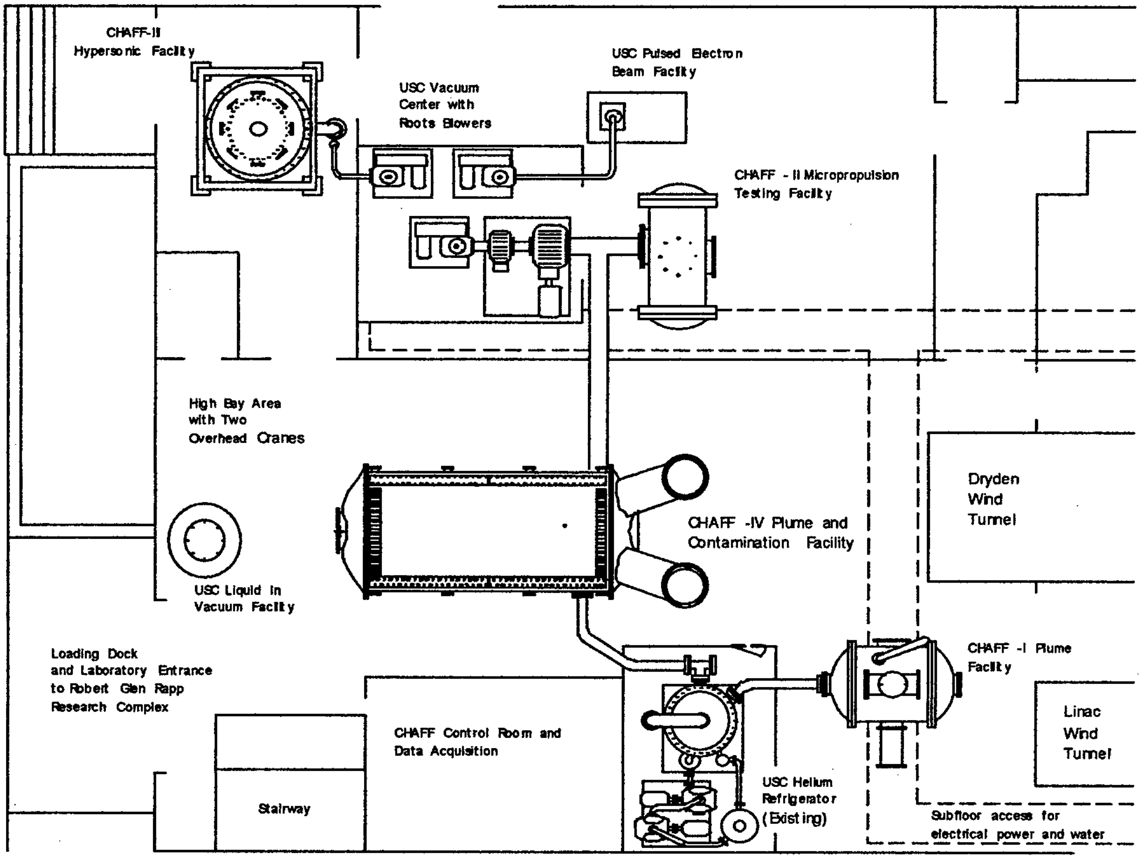


**Figure 5:** Collaborative High Altitude Flow Facility Laboratory Layout and Existing Chambers.

CHAFF-IV is a cryogenically pumped stainless steel vacuum chamber which has been uniquely designed to address thruster-interaction studies for both chemical and ion electric propulsion systems. The design philosophy for CHAFF-IV revolved around an efficient thruster pumping system with a maximized high vacuum pumping area with the introduction of simulated ambient atmospheric flows.[10] As shown in Figures 6 and 7, CHAFF-IV incorporates a total chamber pumping (TCP) concept by lining the entire facility with an array of cryogenically cooled pumping fins. This is done to minimize propellant molecule scattering from facility surfaces which acts to return thruster-borne species to diagnostically important regions of the plume.

CHAFF-IV consists of a cryogenic finned array system enclosed in a 3 m diameter by 6 m long stainless steel vacuum chamber. The cryogenic finned arrangement gives CHAFF-IV approximately 590 $m^2$ of pumping area. The finned array is an opened radial fin system which allows for the operation of high flow rate chemical engines and ion electric thrusters within the chamber as will be discussed in subsequent sections. This configuration allows for reduced sputtering (due to energetic ion impact) and heat transfer to the helium refrigerated panel system by allowing the thruster efflux to initially impinge directly on the liquid nitrogen outer shield. Subsequent collisions of propellant species on the gaseous helium arrays ensures effective pumping by reducing the line of site (solid angle) back to areas of diagnostic importance. The geometrical arrangement effectively increases the maximum acceptable power level of a thruster to approximately 3.5 kW (effective heat load) in CHAFF-IV while still maintaining adequate panel temperatures to ensure pumping.[2]

## 2.1 Radial Fin Cryogenic Pumping System Design

As Eqn. (3) indicates, background gas number densities are minimized by having large available pumping areas ($f_p$ $A_s$). For a given chamber geometry, the pumping rate is maximized by increasing the fraction of

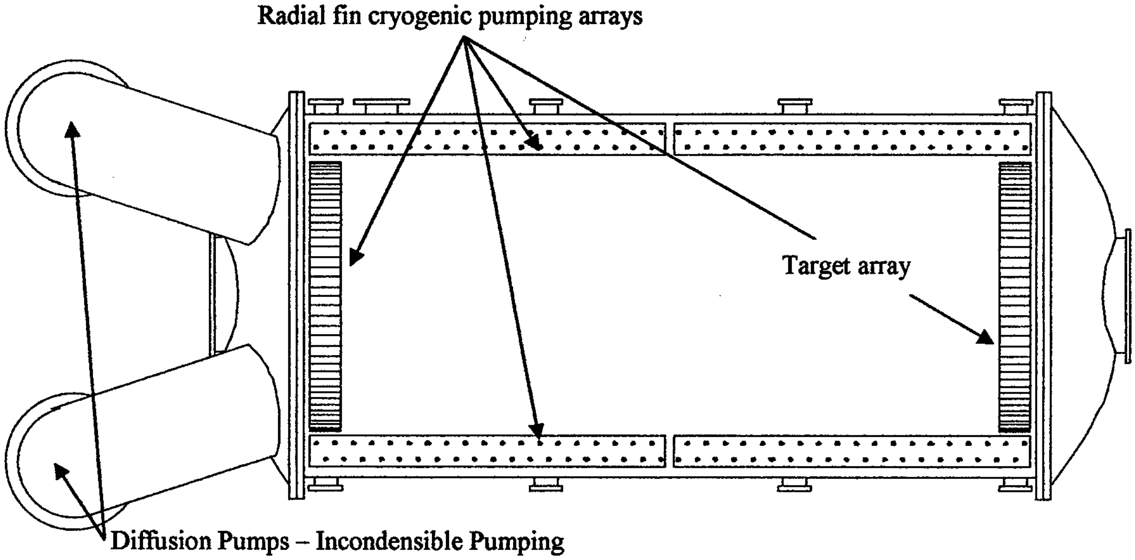


**Figure 6:** CHAFF-IV cryopumping system arrangement showing total chamber pumping concept.

the inner surface area which acts as a pump (i.e. $f_p \geq 1$). This suggests that the highest available pumping rate (minimum background gas pressure) is achieved when the entire inner surface of the vacuum facility is a pumping surface.

For chambers which do not utilize TCP, the maximum $f_p$ is on the order of 0.1 due to the limitations of attaching pumps to the external surfaces of a chamber. Perhaps the only effective way of implementing TCP is through cryogenic pumping. Cryogenic panels can be fitted into a facility quite easily with supply manifolds for the cryogenic fluid (typically helium). A simple cylindrical cryopanel system will allow $f_p$ = 1. However, the radial fin array utilized in CHAFF-IV has an $f_p = 9$. As is evident from Eqn. (3), this can represent a reduction in background gas pressure of approximately 100 times that of a traditional thruster facility.

It is instructive to consider the fraction of efflux from a thruster impinging on a cryopump panel system that is able to return to the thruster vicinity. Such an analysis assuming only neutral components of the flow can prove helpful in designing array geometries to maximize pumping for a given application. The radial fin array fraction of backscattered molecules can be expressed by

$$F_{r,rf} = (1-\eta)\left[\frac{w}{2h}\frac{w}{(w+t)}\left(\frac{D_o}{X}\right)^2 + \frac{t}{(w+t)}\left(\frac{D_o}{X}\right)^2\right] \tag{6}$$

where $\eta$ is the sticking coefficient, w is the fin to fin spacing, h is the length of the fin in the axial direction, t is the fin thickness, X is the distance from the thruster to the cryogenic array, and $D_o$ is the characteristic thruster diameter. Note that Eqn. (6) takes into consideration the finite thickness of the fins as scattering surfaces. For a typical thruster in CHAFF-IV, $F_{r,rf} \sim 10^{-3}$. In other words, only 1 out of every 1000 molecules make it back to a diagnostically important area of interest, a significant reduction over traditional thruster facilities.

Optimization of the pumping efficiency (i.e. reduction of $F_r$) has been achieved in the CHAFF-IV design. For an average CHAFF-IV fin spacing, the geometric term is about 0.16 indicating the immense improvement of this design over traditional facilities which operate on commercially available cryopumps (cryo-tubs). These facilities will not be able to accurately simulate the space environment due to limitations in pumping efficiencies and pump placement.

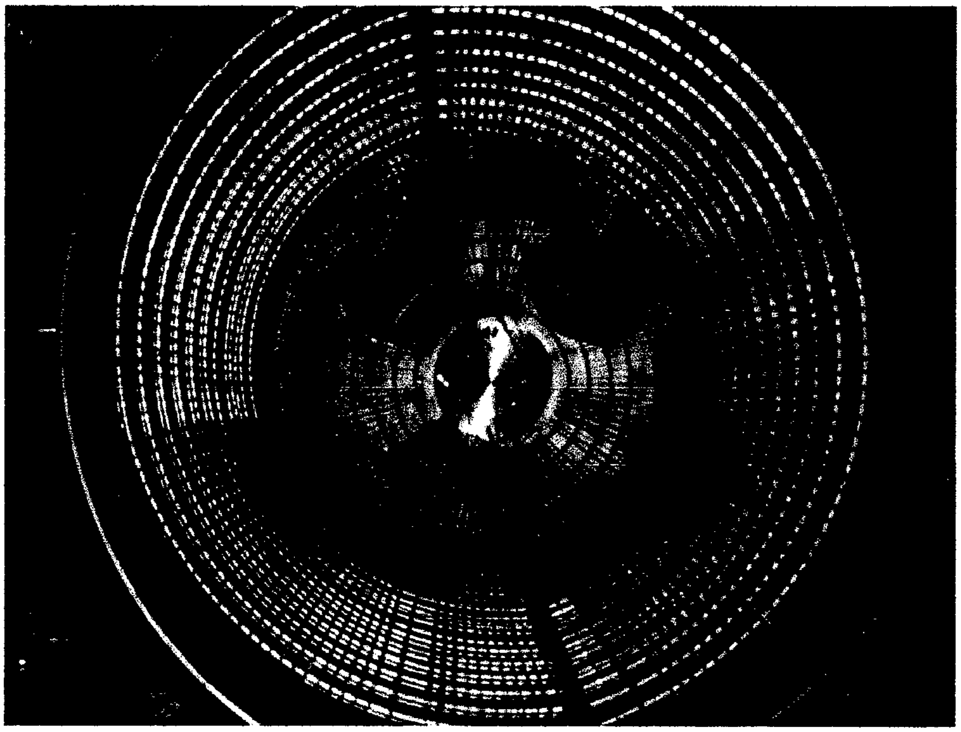

**Figure 7:** Fabricated radial cryopanel array installed in the USC CHAFF-IV facility.

The radial fin configuration offers some other important benefits. First, heat transfer from radiant heat and gas conduction can be minimized by allowing the radiation and energetic propellant molecules to "pass through" the radial fin arrangement and impinge on a liquid nitrogen panel as shown in Fig. 8. The radiant energy is absorbed on the liquid nitrogen panel and the propellant molecules lose a significant fraction of their kinetic energy at the surface liquid nitrogen temperatures. The radial fin configuration can also allow for more pumping surface area over a simple flat panel. Finally, the effects of sputtering for ion electric thruster operation can be minimized since the majority of the energetic ions will impact a graphite film covering the inner surface of the liquid nitrogen panel. After this initial interaction, a relatively slow, neutral molecule will be pumped with the cryogenic fin arrays.

## 2.2 Recent Experimental Results

In order to determine the pumping capabilities of the target section of the finned array (i.e. the array shown at the rear section of the facility in Fig. 7), liquid nitrogen ($LN_2$) was used to cool the panels while $CO_2$ gas was introduced into the chamber. Carbon dioxide pumping at $LN_2$ surface temperatures of ~80 K was used to simulate other gases (including xenon) pumping on 15-20 K surfaces since the sticking coefficients are similar.

For the radial fin pumping configuration, the $CO_2$ was introduced into the chamber through a sonic orifice (diameter = 0.178cm) on the chamber centerline located 79.1cm from the front of the cryogenic finned array. The $CO_2$ flow rates introduced into the facility ranged from 10 to 120 sccm although pumping rate data was obtained for mass flows up to 24,750 sccm. Data was obtained by an ion gauge attached to a Patterson Probe allowing 360 degree rotation along the chamber length and a tunable distance from the side wall to the chamber centerline. Details of the experimental set up can be found in a recent study.[11]

A cryogenic flat panel pumping surface was also tested in the facility in an attempt to assess any pumping improvement afforded by the finned geometry. In this case, the sonic orifice was adjusted to a distance of 110.2 cm from the panel to maintain constant coverage (~90%) from the sonic orifice between the two tests. In both experiments, one of the two available 1.0 meter diameter diffusion pumps was used to pump

incondensible gases in the facility. The effective pumping speed of the diffusion pump on $CO_2$ gas was measured to be between 10,600 and 11,800 L/s with a theoretical maximum of about 20,000L/s.

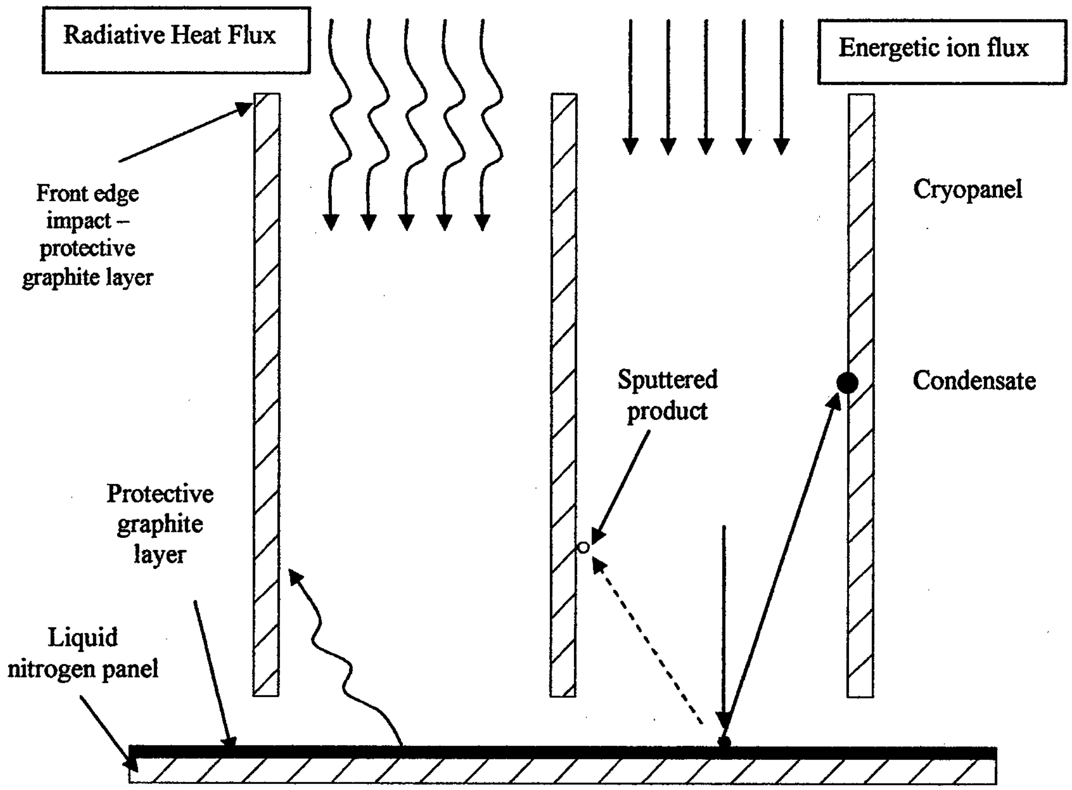


**Figure 8:** Radial fin array geometry. a) Radiation interaction; b) ion bombardment.

Based on pressure data, pumping rates for the radial fin were determined and are shown in Fig. 9 as a function of mass flow rate. As indicated, the pumping rate ranges from approximately 0.65 to 1.25 x $10^6$ L/sec. For an indicated mass flow rate of 24,750 sccm, the measured pumping rate was about 2.6 x $10^6$ L/sec.

The pressure at the Patterson probe as a function of mass flow at various radial locations was obtained for both the radial fin and flat panel. The general trends in the data indicate that the radial fin array provides more efficient pumping than a simple flat panel array.[11] For neutral gas flows at elevated temperature, the radial fin array backed by a $LN_2$ shield would perform optimally. The sticking coefficient increases for a given surface temperature as the gas temperature decreases. When the radial fin array is at 15-20 K backed by a $LN_2$ shroud, the energetic molecules will accommodate (at least partially) to the 77 K surface. After scattering from the $LN_2$ surface with a velocity distribution function characteristic of the surface temperature, the effective sticking coefficient on the radial array will be lower thereby increasing the pumping efficiency.

Figure 10 shows a radial profile for the fin and the flat panel pumping configurations for a mass flow of 20 sccm. Again, this data indicates that the finned array is more effective than a flat panel over the range of fin spacing used in this design. In some cases, the pumping ratio reaches a factor of more than 4.

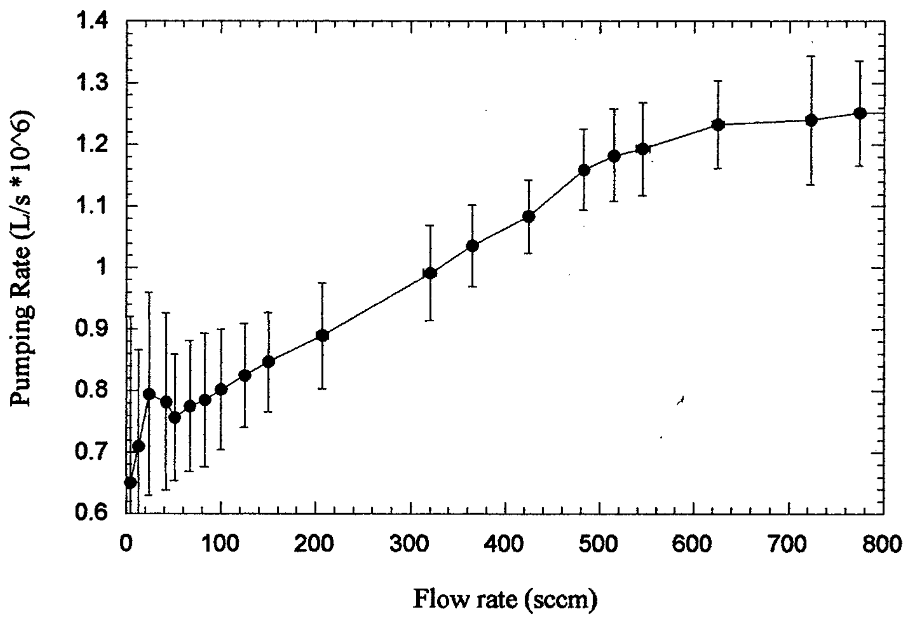


**Figure 9:** Radial Fin array pumping rate as a function of mass flow rate. (5.6% of entire array activated)

The performance of the radial finned arrays obtained in recent studies indicates the importance of this unique geometrical pumping configuration. Further improvements in the capacity of the cryostat are required and justified in an attempt to obtain meaningful interaction data, and CHAFF-IV is the only facility in the world that has the potential to provide truly accurate thruster interaction data.

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### 3.2 Ambient Atmospheric Interactions: Simulation of the Low Earth Orbit Environment

In the future, atmospheric species sources will be utilized in CHAFF-IV to investigate a wide variety of thruster interaction phenomenon. Applications to plume signatures, spacecraft contamination, gas-surface interactions, spacecraft glow, and material degradation are all of great interest to defense and commercial sectors. Environments of interest for thruster interaction studies are:

- low-Earth orbit atomic oxygen (prevalent species between 150 and 600 km)
- other energetic atomic and molecular species
- ionospheric plasma
- solar energy (ultra-violet, visible, infra-red)

The simulation of atmospheric constituents at appropriate flux and energy levels is the topic of current research at USC and other institutions.

Regardless of the technical difficulties in reproducing atmospheric flows, it is obvious that these systems will drive additional facility pumping requirements. The introduction of these highly energetic flows will require similar pumping requirements as the thrusters that are operating simultaneously. Many of the sources will also require differential pumping from the main chamber to assure flow quality. The addition

of atmospheric simulation in requires additional pumping capacity to augment the original CHAFF-IV cryogenic system.

**3.3 Existing Facilities and Equipment at USC**

CHAFF is a complex of four high altitude chambers with supporting diagnostic and computational data collection equipment available. The laboratory layout is shown in Fig. 5. CHAFF-I is a cryogenically pumped small plume and micropropulsion system chamber. The facility is approximately 2 m in diameter with two cylindrical flat panel pumping arrays. CHAFF-I also has two large diffusion pumps (8500 L/s) and a turbomolecular pump (1000 L/s) to remove incondensible gases. This facility is outfitted with several diagnostic packages including an electron beam, xcimer/dye laser combination, quadrupole mass spectrometer, optical spectrometers, and a full chamber micro-positioning traverse system.

CHAFF-II is a hypersonic flow facility with liquid nitrogen cryopumping finned array panels. This pumping system is capable of pumping high temperature carbon dioxide or iodine flows. It is backed by a 0.5 m diffusion pump (2,500 L/s). The inner surface of the facility is Teflon coated to protect against corrosive gas attack.

CHAFF-III is a micropropulsion test facility which is backed by a large Roots Blower system. The facility is currently used as instrumentation check-out facility.

CHAFF-IV is a cryogenically pumped stainless steel vacuum chamber which has been uniquely designed to address thruster-interaction studies for both chemical and ion electric propulsion systems. CHAFF-IV incorporates a total chamber pumping (TCP) concept by lining the entire facility with an array of cryogenically cooled pumping fins to minimize propellant molecule scattering from facility surfaces. The facility consists of a cryogenic finned array system enclosed in a 3 m diameter by 6 m long stainless steel vacuum chamber. The cryogenic finned arrangement gives CHAFF-IV approximately 590 $m^2$ of pumping area. The finned array is an opened radial fin system which allows for the operation of high flow rate chemical engines and ion electric thrusters within the chamber as will be discussed in subsequent sections.

**4 CRYOGENIC PUMPING SYSTEM ENHANCEMENT PROCURED BY THE DURIP AWARD**

The CHAF facility's original cryogenic pump is a refurbished 1950's era helium refrigerator manufactured by the Arthur D. Little Corporation. The original USC cryostat provides gaseous helium pumping for both CHAFF-I and CHAFF-IV. Although it has been extremely reliable in the past, it provides rather low maximum heat load characteristics, and its operation is somewhat labor intensive. **This system is capable of providing gaseous helium at 20 K with an incident heat load on the cryofin system of up to 200 Watts.**

The design of the CHAFF-IV cryo-finned array possess three important problems for the operation of the original cryostat. First, the limited heat load capacity at 20 K only allows thrusters with operating heat loads less than 3,500 W to be effectively tested. **The ability of the CHAFF-IV cryopumping system to effectively pump thrusters plumes with higher power than the heat load capacity of the cryostat is detailed in previous sections (see Fig. 8). The capability of pumping thruster system flows with significantly higher heat loads was originally envisioned for CHAFF-IV through the use of liquid helium augmentation supplied by 200 L dewars.** Although this contingency was designed for in the cryo-fin array construction, it is an extremely expensive proposition for tests beyond several minutes.

Second, the cool down time of the existing arrays is approximately 24 hours due to the mass of the panels to be cooled to 20 K. This implies that three work shifts are required by competent personnel to oversee CHAFF-IV's operational readiness. Also, the turn-around time between experiments is limited by this factor. Finally, the most important limiting factor in the use of the existing cryostat system on CHAFF-IV is that pumping requirements brought on by future additions to the facility (such as atmospheric simulation sources) cannot be met.

The new cryostat procured with the present DURIP provides higher capacity and more reliable CHAFF-IV pumping for both chemical and electric thrusters that will allow accurate thruster interaction studies to be performed through the addition of a commercially available cryostat. **The Linde Corporation (formerly Process Systems International) cryostat is a well established, proven product for this application, and a similar system is currently being used on the Air Force Research Laboratory's Electric Propulsion Lab.** The Model 1620 cryostat (1620 cryostat) and associated compressor system is capable of providing gaseous helium at 20 K with an incident heat load up to 1000 W. This cryostat working in conjunction with the original USC helium refrigerator effectively increases the pumping capacity by a factor of five which is enabling for contamination and ambient atmosphere interaction studies.

Working in conjunction with the original USC cryostat, thrusters with incident heat loads up to approximately 12.5 kW would be effectively operated in CHAFF-IV with the pumping configuration shown in Fig. 11. The 1620 cryostat is used to pump the cryo-fin array with is directly impacted by the thruster effluents. The original USC cryostat is used to pump the finned array in the thruster backflow, a critical region for thruster-spacecraft interaction studies. **Many existing chemical thrusters operate with heat loads in the 10 kW range.** There is also a trend in higher power ion electric and Hall thrusters for orbital transfer missions. **The ability to test these high power systems for contamination potential will be critical in determining the overall effectiveness of electric propulsion used as orbital transfer vehicles. This allows the operation of a single thruster or group of interacting thrusters with heat loads approaching 20 kW.**

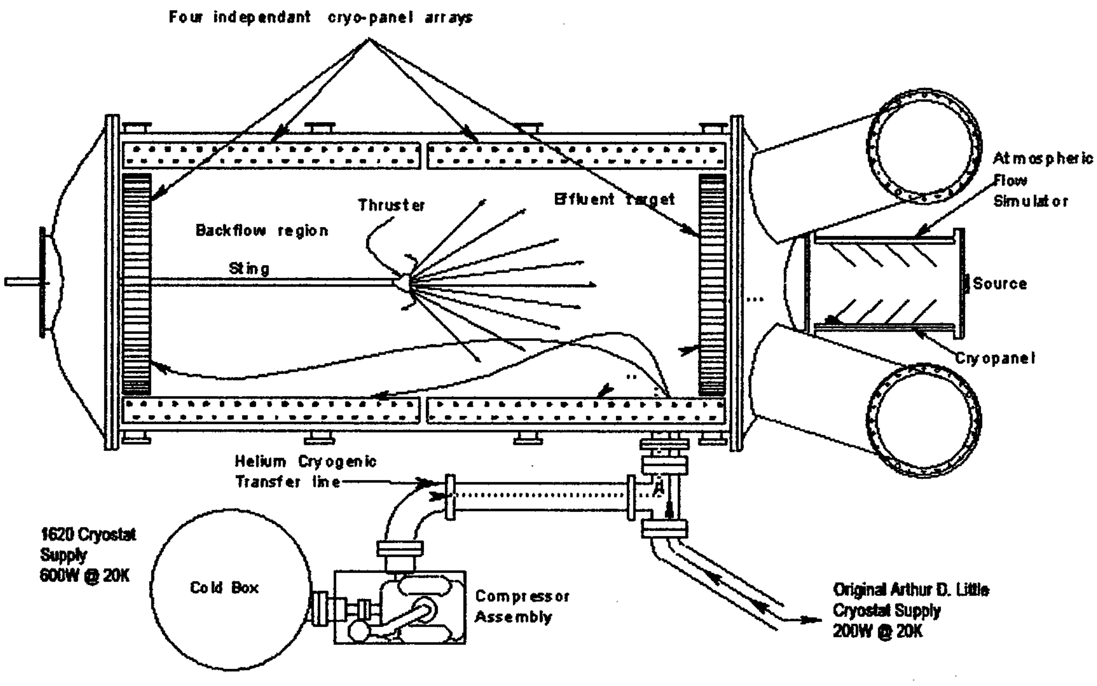


**Figure 11:** CHAFF-IV configuration showing cryostat arrangement with original and new helium refrigerators for a future atmospheric simulation study.

As mentioned earlier, the addition of ambient atmosphere simulation also burdens the facility's pumping system. For some simulated flows, the pumping requirements can begin to approach those of a firing thruster system. The addition of the 1620 cryostat enables simulated flows of atomic oxygen and ionospheric plasma to be added in the near future. Solar simulation can also be taxing on the pumping system due to the incident photon energy on the cryogenic arrays. In some applications, it is important to simulate all the appropriate environments simultaneously to account for synergistic effects.

In order for the 1620 cryostat to work effectively, a cryogenically engineered transfer line is required to introduce the gaseous helium into the CHAFF-IV radial fin arrays. Figure 12 shows the transfer line

arrangement for the 1620 cryostat. This cryo-transfer line is designed to minimize heat transfer from the surrounding environment. The transfer line is pumped to high vacuum levels (< $10^{-6}$ Torr) by a diffusion pump to eliminate convective heat transfer issues. Diffusion pumps are used due to their reduced cost over turbomolecular pumps at equivalent pumping speeds. The diffusion pump is isolated from the transfer line by a liquid nitrogen cold trap to minimize heat transfer and prevent oil backstreaming into the transfer line. A liquid nitrogen panel is fitted inside of the transfer line to limit the radiative heat load to the gaseous helium supply tubes going to CHAFF-IV cryo-pumping arrays. Teflon spacers are used to ensure proper spacing of the supply tubes in the transfer line. The gaseous helium return lines bring gaseous helium from the cryo-fin arrays back to the cryostat in a closed cycle operation. The return temperature of the gaseous helium is generally greater than 20 K which necessitates their remoteness from the supply lines.

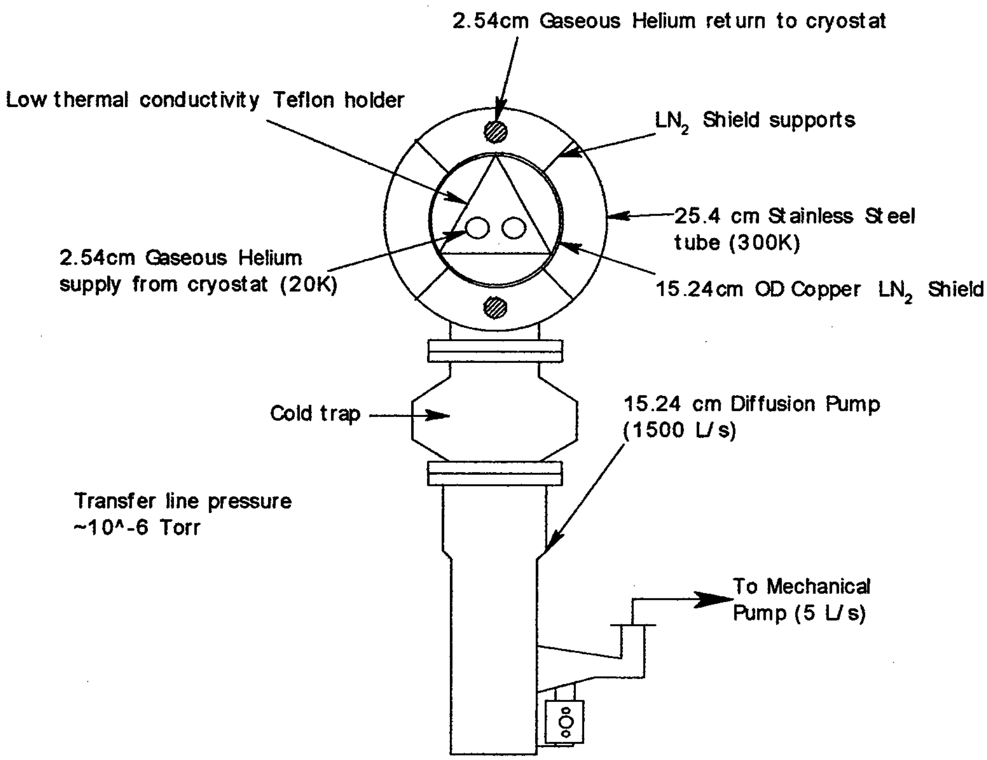


**Figure 12:** Cryogenic helium closed loop transfer line from cryostat to CHAFF-IV radial cryo-fin arrays.

The CHAFF-IV radial cryo-finned arrays are a vast improvement over traditional cryopumping arrangements based on the results obtained for the pumping rate and efficiency presented in earlier sections. For the first time since the dismantling of the Jet Propulsion Laboratory's Molecular Sink Facility over 20 years ago, there is an opportunity to obtain truly meaningful spacecraft-thruster interaction data. For the first time in the history of ground-based experiements, there is a possibility for a facility to provide extremely accurate, simulated atmospheric flow with an operating thruster simultaneously.

Facility Engineer; Mr. Robert Smith is the cryostat facility engineer for CHAFF. He has 35 years of experience working with mechanical systems and extensive experience working with the USC facilities and cryostat. Mr. Smith is currently refurbishing the existing CHAFF helium refrigerator.

## 5 STATUS OF 1620 CRYOSTAT INSTALLATION

The 1620 cryostat was ordered on 2/21/02 from Pro-Quip Corp. (now Linde Corp.) with a delivery date of 12/21/01. Due to technical difficulties (each unit is manufactured to order) the delivery slipped, eventually to 7/10/02. During this process there was a price reduction which enabled us, for the original price, to increase the cryostat's capacity ( by being able to move up to a larger compressor section), resulting in the

1000 W capacity compared to the originally proposed 600 W. After a series of delays the compressor was delivered on 7/10/02.
Due to the late delivery the anticipated acceptance tests of the 1620 cryostat had to be delayed, because of conflicts with other Air Force sponsored experiments in Chaff IV causing a personnel availability problem. The acceptance and initial shake-down tests are currently proceeding as illustrated in Fig 13.

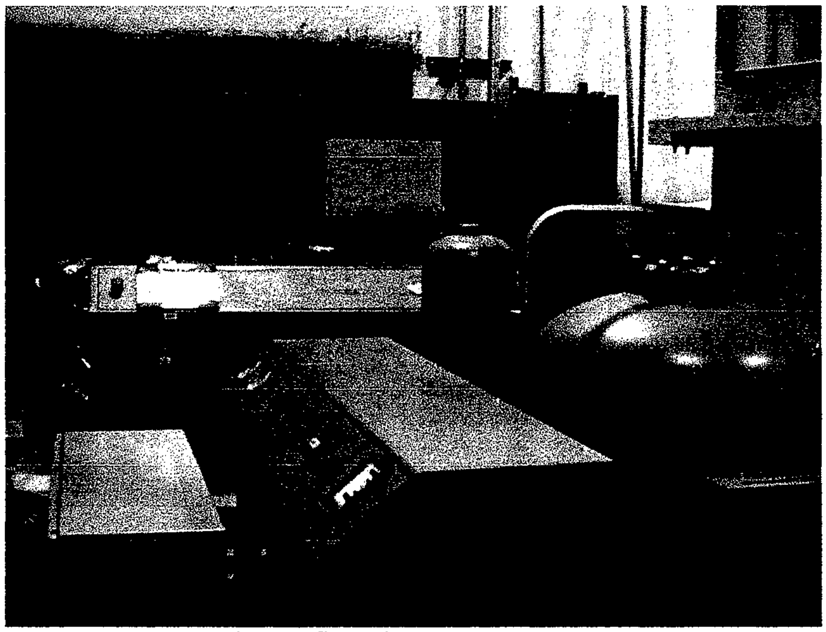

**Figure 13:** Cryostat, acceptance testing configuration.

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